Flywheel Power System Trade Studies

Flywheel Workshop

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Outline

- Technology Projections
- Generic Mission Studies
  - LEO
  - GEO
- Recent Trade Studies
  - Space Based Radar
- Observations/Feedback
- Challenges to Flywheel Industry

Technology Projections

	State-of-the-Art	Near Term	Future
Power Generation	• 19% GaAs/Ge rigid arrays, 40 W/kg	• 23% GaInP/GaAs/Ge SCARLET, 7:1 Conc Ratio, 60 W/kg array • 9% α-Si flexible blanket, 100 W/kg • 25% SD-Brayton w/TES, 10 W/kg system	• 35% 3-4 Junction MBG, 100 W/kg, rigid or conc array • 15% CIS thin film blanket, 300 W/kg • 35% SD-Stirling w/TES, 15 W/kg system
Energy Storage	• 25 Whr/kg NiCd, 15% LEO DOD, 60% RT efficiency • 35 Whr/kg CPV NiH2, 35% LEO DOD, 80% RT eff	• 100 Whr/kg Li-Ion, 35% LEO DOD, 90% RT efficiency • 44 Whr/kg Flywheels, 89% DOD, 92% RT efficiency	• 250 Whr/kg Li-Polymer, 60% LEO DOD, 90% RT eff • 66 Whr/kg IPACS Flywheels, 89% DOD, 92% RT eff
Power Mgmt & Distribution	• 28 Vdc, 80-90% efficiency, 40-50 W/kg	• 120 Vdc, 85-95% efficiency, 125 W/kg	• Integrated Bus, 85-95% efficiency, 250 W/kg

LEO Energy Storage Comparison

Mission: 5 kW LEO Satellite, 100 min orbit, 35 min eclipse

	NiH2	Li-Ion	Flywheels
Storage Wh/kg	35	100	44
DOD	35%	35%	89%(1)
RT efficiency	80%	90%	92%
Charge/discharge efficiency	90%	90%	N/A
Charge/discharge mass, W/kg	200	200	N/A
Del'd energy, kWh	2.9	2.9	2.9
Stor'd energy, kWh	9.3	9.3	3.3
Req'd energy, kWh	4.5	4.0	3.2
Array power(2), kW	10.2 (100%)	9.7 (95%)	8.8 (87%)
Storage Mass, kg	289 (100%)	118 (41%)	74 (26%)

(1) 89% DOD relates to 3:1 flywheel speed ratio
(2) 90% PMAD efficiency assumed

GEO Energy Storage Comparison

Mission: 15 kW GEO Satellite, 1440 min orbit, 70 min eclipse

	NiH2	Li-Ion	Flywheels
Storage Wh/kg	35	100	44
DOD	70%	70%	89%(1)
RT efficiency	80%	90%	92%
Charge/discharge efficiency	90%	90%	N/A
Charge/discharge mass, W/kg	200	200	N/A
Del'd energy, kWh	17.5	17.5	17.5
Stor'd energy, kWh	27.8	27.8	19.7
Req'd energy, kWh	27.0	24.0	19.0
Array power(2), kW	18.0 (100%)	17.8 (99%)	17.6 (98%)
Storage Mass, kg	869 (100%)	353 (41%)	447 (51%)

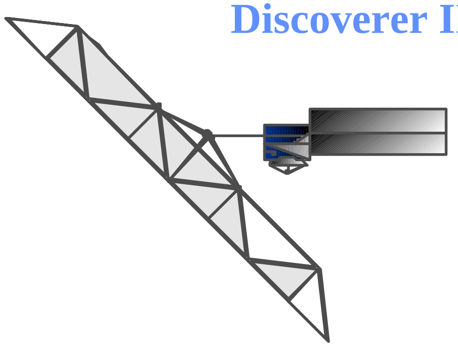
(1) 89% DOD relates to 3:1 flywheel speed ratio
(2) 90% PMAD efficiency assumed

Recent Trade Studies

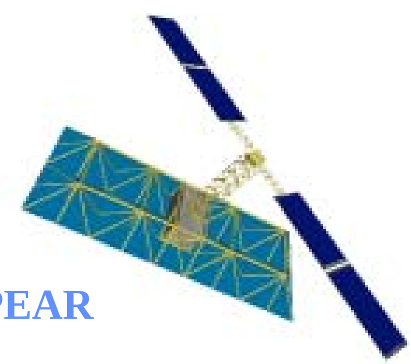
- Space Based Radar
  - SPEAR & SPEAR U/X (AF)
  - Discoverer II (DARPA)
- Reusable Launch Vehicle (MSFC)
- GEO Communications Satellites (Hughes)
- International Space Station (JSC)
- Space Science - Team X (JPL)
- Human Mars Mission (JSC)
- Space Solar Power (NASA HQ)

SBR Concepts

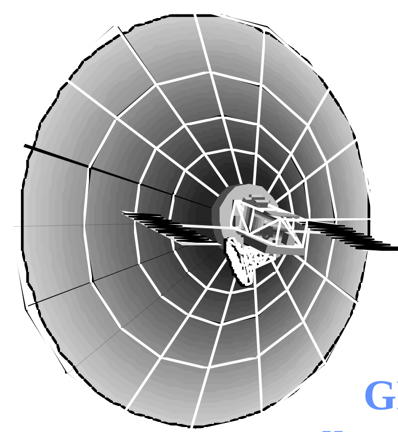
	Discoverer II	SPEAR	SPEAR UX	Techsat 21	MEO	Mitre Bistatic	
Sponsor	DARPA	AF-PL	AF-PL	AF-PL	AF-Rome	AF	
Orbit	770 km	850 km	850 km	700-800 km	10371 km	GEO Illum	LEO Rcvr
Antenna	5x8m	6x22m	6x44m	2x2m	50m dia	80m dia	6x44m
Frequency	X-band	X-band	X + UHF	X-band	L-band	S-band	X-band
Constellation	24 Sats	36 Sats	80 Sats	35x16 Sats	16 Sats	3 Sats	75 Sats
Standby Pwr	0.4 kWe	1.2 kWe	1.3 kWe	0.1 kWe	4.9 kWe	-	?
Radar Pwr	4.8 kWe	26.2 kWe	29.9 kWe	1.0 kWe	119.0 kWe	-	?
Radar Duty	10%	30%	30%	22%	36%	100%	26%
Avg Pwr	0.8 kWe	8.7 kWe	9.9 kWe	0.3 kWe	46.0 kWe	60 kWe	5 kWe
Timeframe	2003	2015	2025	>2005	>2010	?	?
S/C Mass	1500 kg	4400 kg	6500 kg	100 kg	?	18000 kg	?
S/C Cost	$100M	$150M	$180M	$10M	?	?	?



Discoverer II



SPEAR

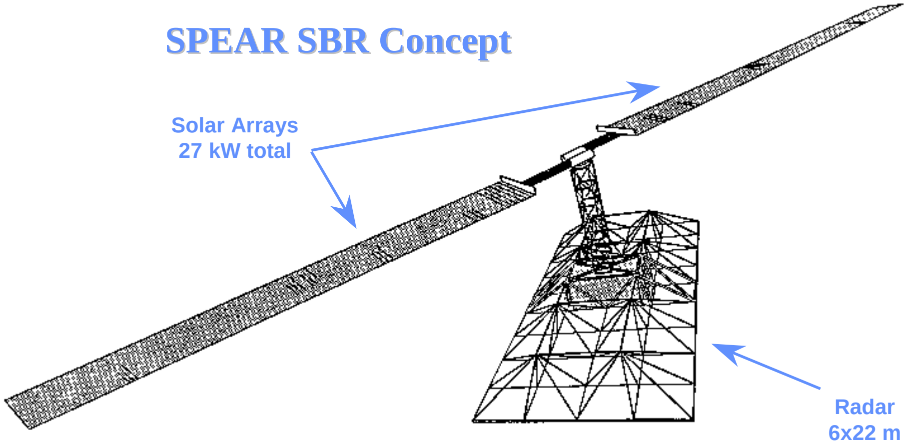


GEO Illuminator

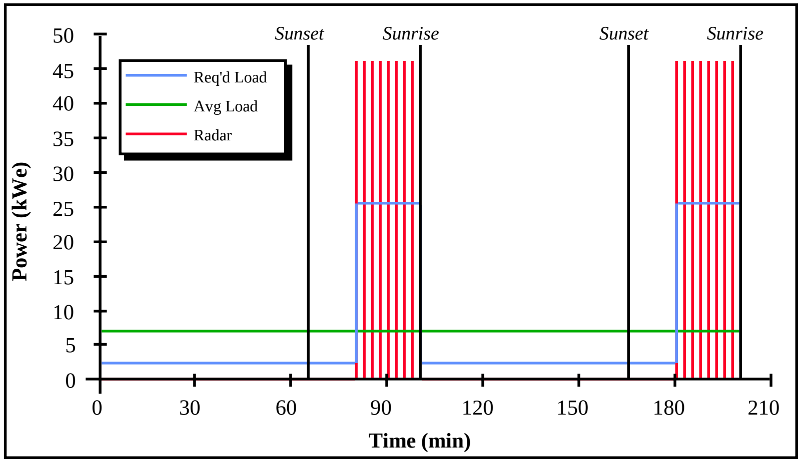
SPEAR & SPEAR U/X

- SPace Electronically Agile Radar
  - AF Phillips Lab Concept (SBR IPT-Dr. Yolanda King)
  - Possible AWACS Replacement (High Res. SAR, GMTI, AMTI)
  - Near Term Focussed on Risk Reduction Activities
  - Power is Critical Technology
- LeRC Initiated Trade Study to Examine Solar Dynamic Applicability
  - SD Performance, Cost, Design, and Program Definition
  - Boeing (Seattle) Task Order
  - Independent Technology Review

SPEAR SBR Concept



SPEAR Power Profile



Performance Comparisons

SPEAR & SPEAR U/X

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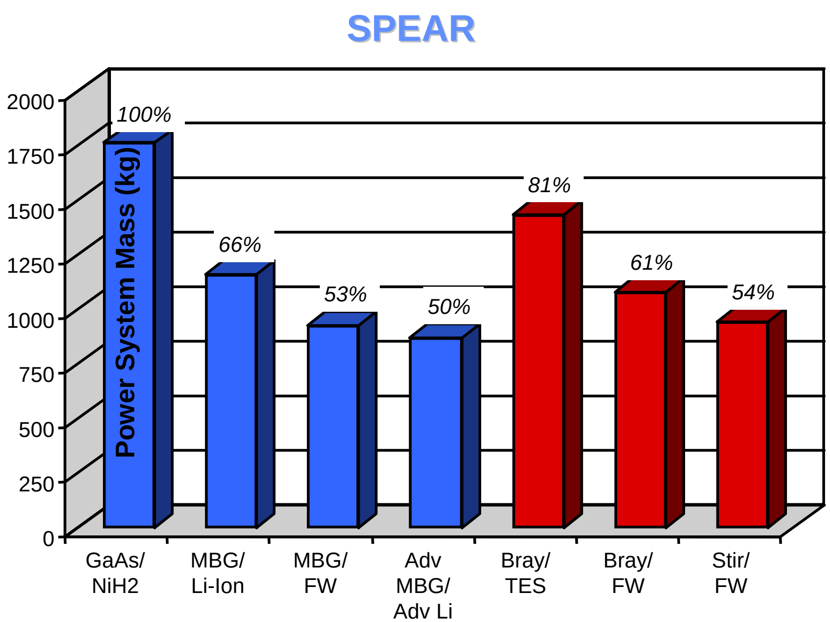
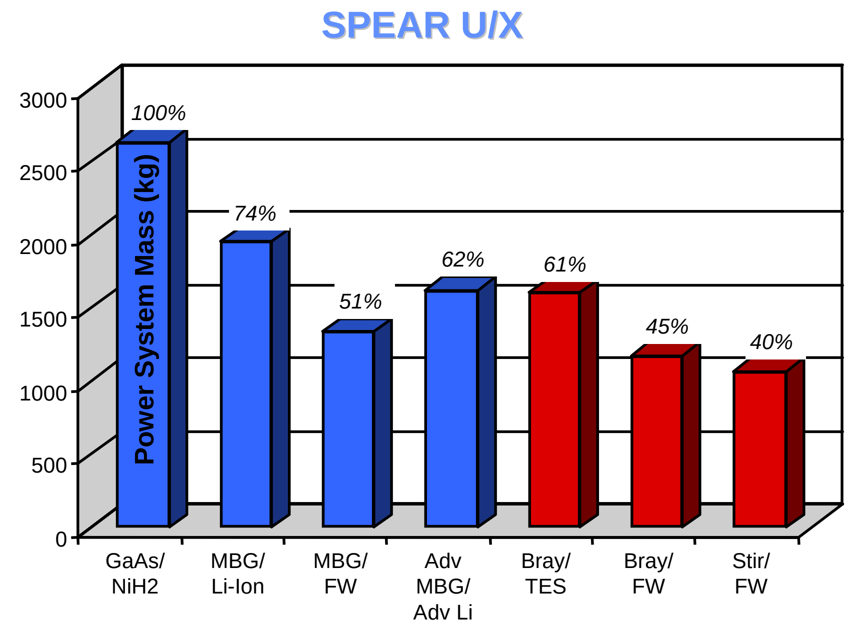




- **33-60% Mass Savings over SOA with Advanced Power**
- **Similar Savings in Deployed Area, Stowed Volume**
- **Benefit to Mission is Increased Mass & Volume for Payload**
- **Development Costs for Advanced Power are often Offset by Reduced Launch Vehicle and/or Integration Costs**
- **Large Satellite Constellations (i.e. SBR) are Excellent Candidates for Advanced Technology due to Long Term Recurring Cost Savings**

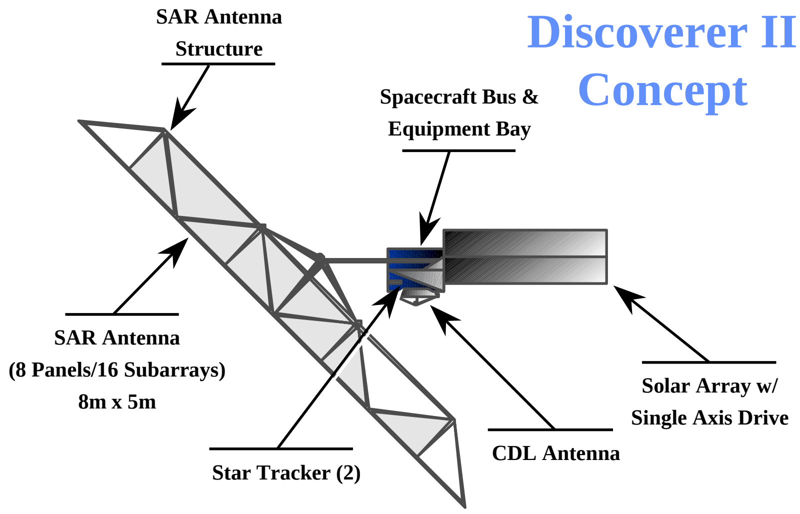
Discoverer II

- **Joint DARPA/AF/NRO Program**
  - **Formerly STARLITE**
  - **Develop High Resolution Synthetic Aperture Radar (SAR), Ground Moving Target Indication (GMTI)**
  - **2003 Flight of (2) Demo Sats**
  - **2007+ Objective System (24-48 Satellite Constellation)**
- **LeRC Requested to Provide Power Technology Support**
  - **Space Act Agreement with DARPA (2/98)**
  - **Trade Study Initiated (3/98)**
  - **Compare Options on Performance, Cost**
  - **Develop Power Technology Roadmaps for DARPA**

Orbit:
770 km, 55° inclination
100.2 minute period
35.0 minute maximum eclipse

Spacecraft: (Variations)
400 Watt standby (nominal). . .800 W (2x)
4.8 kWe radar (peak). . . . . . . .9.6 kW (2x)
10 minute peak duty cycle. . . . 20 min (2x)
120 Vdc bus voltage
1-2 yr life (Demo), 7 yr life (Objective System)
2000-2005 technology cut-off

Discoverer II Concept



Technology Options

Discoverer II

Power Generation	Energy Storage
Photovoltaic	**Electrochemical**
Silicon	NiCd
GaAs	IPV NiH2
Multi-band Gap (GaInP/GaAs)	CPV NiH2
RAINBOW	NiMH2
SCARLET	Liquid Li-Ion
SOLARCON	Solid Li-Polymer
a-Si	NaS
CuInSe (CIS)	**Mechanical**
Solar Thermal	Flywheels
Brayton	**Thermal**
Stirling	LiFCaF2
Rankine	LiF
Thermionic	
AMTEC	
TPV	

Power System Trade Matrix

Pwr Generation	Energy Storage				
	NiH2	Li-Ion	NaS	FW	TES
PV GaAs	Ref	◄	◄	◄	
PV MBG	◄	◄	◄	◄	
PV Scarlet	◄	◄	◄	◄	
PV α-Si	◄	◄	◄	◄	
SD Brayton				◄	◄
SD Stirling				◄	◄

Filters:
Power Level
Performance Potential
Tech Cut-off Date
Similarity

Power System Sizing

Discoverer II

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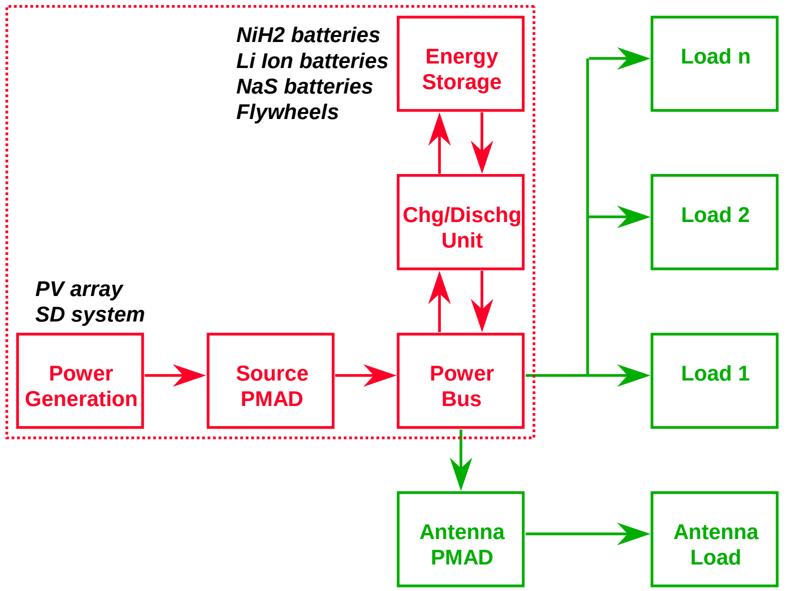
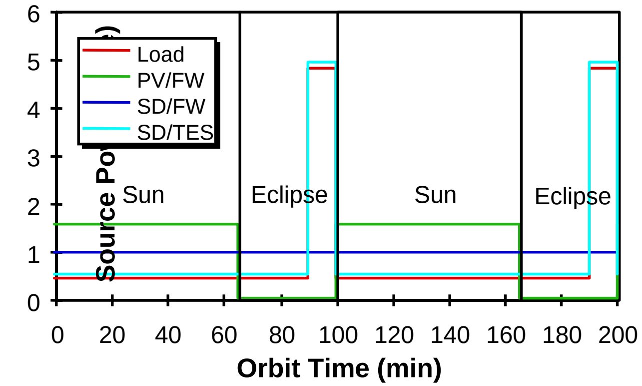
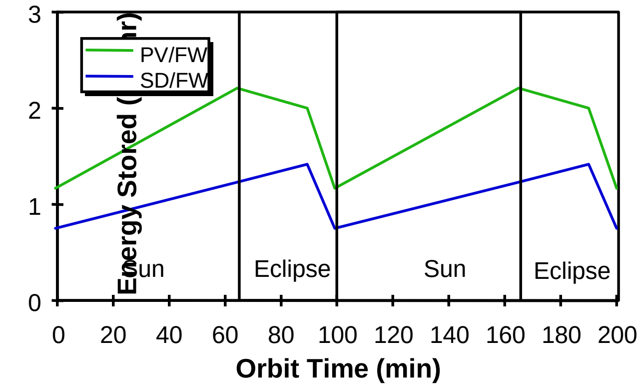


Power System Block Diagram

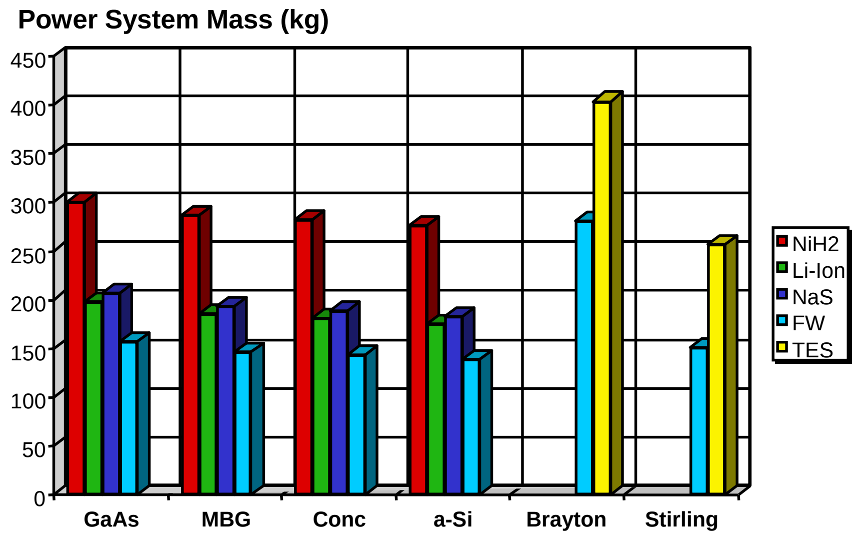


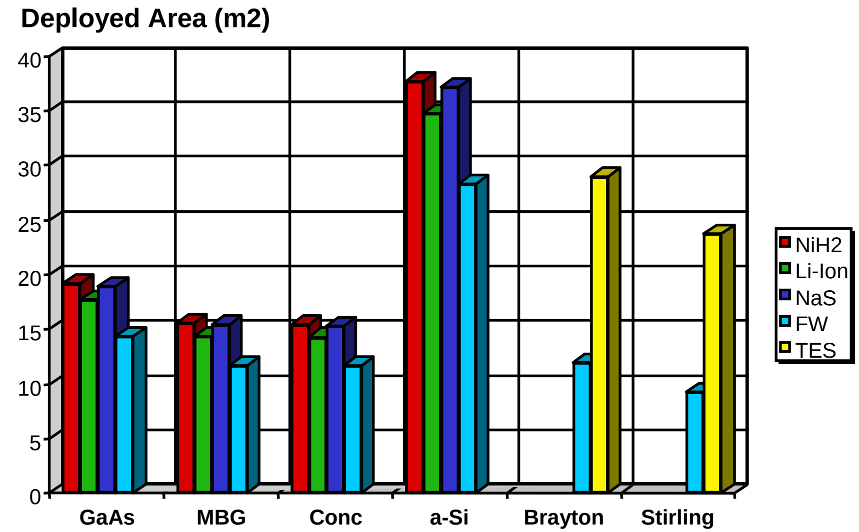


	Power Generation		Energy Storage	
	Bus Power, kW	EOL Source Power, kW	Delivered Energy, kWh	Stored Energy, kWh
PV/NiH2	2.08	2.45	1.03	3.48
PV/Li-Ion	1.90	2.25	1.03	3.48
PV/NaS	2.04	2.40	1.03	3.00
PV/FW	1.53	1.84	1.03	1.15
Brayton/FW	0.97	1.15	0.65	0.74
Stirling/FW	0.97	1.22	0.65	0.74
Brayton/TES	4.90	5.26	-	-
Stirling/TES	4.90	5.78	-	-

Source Power and Energy Storage Size vary with Technology

Performance Comparison
Discoverer II

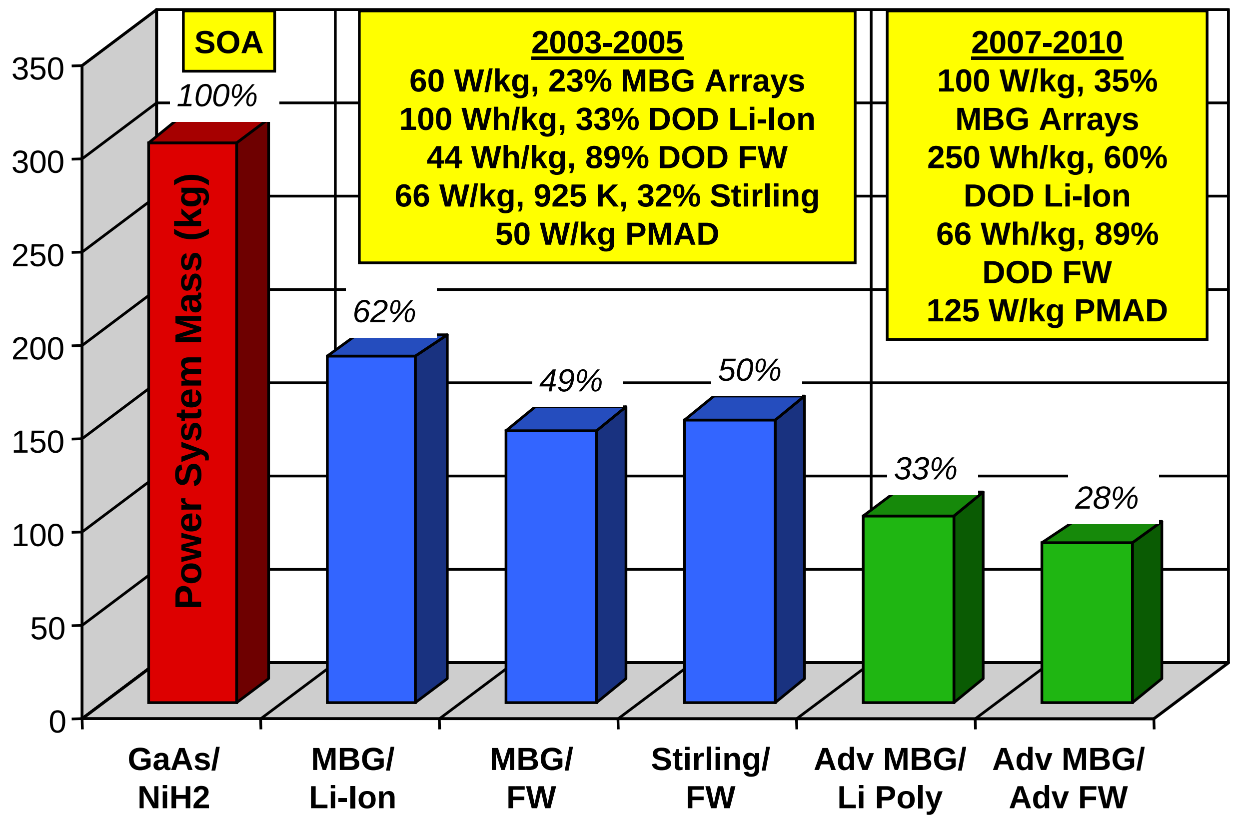




Conclusions:

- **Largest Mass Savings Realized with Advanced Energy Storage**
- **Flywheels offer 48% System Mass Improvement over NiH2**
  - **Key is high roundtrip efficiency**
  - **Result is reduction in source power, storage size, and PMAD**
  - **Additional satellite benefit is elimination of separate ACS**
- **Li-Ion also Attractive Option due to High Energy Density**
- **High Efficiency (MBG or Conc) Arrays provide 18% Area Reduction**
- **a-Si provides 33% Array Mass Savings, but 2x Area Penalty**
- **Stirling/FW offers 50% Mass Savings over GaAs/NiH2 and Minimum Deployed Area**

Beyond Discoverer II



Deployed Area, m2...	19.2	14.4	11.7	9.3	9.3	7.6

Observations

- **Advanced power system technologies can significantly reduce the mass and cost of future satellites**
  - **Mass savings ⇨ 1) Greater payload capability, or 2) Smaller launch vehicle, or 3) More satellites per launch**
  - **Recurring cost savings is result of smaller units, fewer parts, more simple production process, less complicated systems**
  - **Dual functionality of IPACS Flywheels provides added benefit**
- **Energy storage is usually key to reducing system mass**
  - **More than just energy density!**
- **System trade studies provide mechanism for identifying:**
  - **Technologies that offer greatest mission benefit**
  - **Key performance parameters**
- **Benefit of advanced technology is more easily recouped in large satellite constellations like SBR**
  - **Higher DDT&E costs offset by recurring cost savings**

Flywheel Challenges

- Overcome "Standard Operating Practices" of Satellite Manufacturers (i.e. PV arrays + Batteries)
- Provide Overwhelming Reasons for Missions to Consider Alternative to Batteries
  - Lower Mass
  - Reduced Source Power
  - Longer Life
  - Less Complicated
  - Dual Functionality (i.e. IPACS)
- Demonstrate Technology in Ground Testing & Flight Experiments
  - End-to-End System Demos
  - Substantiate Performance Claims
  - Alleviate Safety Concerns
- Technology Development and Demonstration is more Important than Continual Performance "Tweaking"